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空中超音波触覚が擬似硬さ知覚に与える影響の調査

Investigating the Impact of Airborne Ultrasound Tactile Feedback on Perceived Intensity of Pseudo-stiffness

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概要: Pseudo-haptics can make people perceive haptic sensations solely through visual cues, while ultrasound can induce tactile sensations in mid-air without contact. Both methods don ’ t require users to wear devices. This study examines whether ultrasound tactile sensation can strengthen pseudo-stiffness intensity.

キーワード： 疑似触覚、超音波触覚、固さ知覚

1. Introduction

Haptics is a promising modality due to its potential applications, such as improving game enjoyment and expanding the sense of immersion in virtual reality (VR) experiences. To present haptic sensations, physical contact with a mechanical device is typically required, and this requirement sometimes limits users’ natural body movement.

Pseudo-haptics is one of the noncontact haptics technologies inducing haptic perception solely through visual cues without any physical contact [1]. In VR space, altering the avatar’s body movements can induce various haptic perceptions. For example, if the displacement of the virtual finger (virtual button) is smaller than the actual finger movement, the virtual-real discrepancy induces an illusion of increased stiffness. Such a ratio between the user’s actual movements and the altered virtual movements shown in the VR space is called the Control-to-Display (C/D) ratio. It is known that decreasing the C/D ratio can induce stronger force perception (the pseudo-stiffness is increased in such a pushing button situation).

Although the perceived intensity of pseudo-haptics can be intensified by decreasing the C/D ratio, it is known that the maximum force intensity is limited [2]. While the evoked pseudo-force intensity can be increased by decreasing the C/D ratio, users cannot perceive the pseudo-force as expected with an extremely low C/D ratio because the visual feedback becomes unnatural (i.e., the discrepancy between modulated body movements and real body movements becomes too large). As an example, a previous study showed that the perceived softness of objects could be increased by up to 28.1% and their stiffness by up to 8.9% [3].

To expand the perceived intensity of induced pseudo-force perception, some previous studies proposed a combination of pseudo-haptics and other haptic displays [4, 5]. Noto et al. reported that pulling sensation illusion with asymmetric vibration can enhance pseudo-force perception[4]. Hirao et al. also reported that tendon vibration can enhance pseudo-weight perception [5]. However, these methods require users to wear devices. This conflicts with pseudo-haptics’ advantage, inducing haptic perception without mechanical contact.

To intensify pseudo-force perception without contacting devices, this study proposes simultaneously using pseudo-haptics and ultrasound noncontact tactile stimulus [6]. By focusing ultrasound, noncontact physical force, called acoustic radiation force can be generated at the focus. A noncontact tactile stimulus can be presented by forming the focus on the human skin.

As an example of stimulation, we focused on and preliminarily evaluated the effect of ultrasound tactile stimulus on the pseudo-stiffness of virtual buttons. In the experiment, we developed a button UI in VR space. The pseudo-stiffness of the virtual button was controlled by varying the C/D ratio from 0.5 to 1.5. Moreover, an ultrasound noncontact tactile sensation was presented to the participants’ finger pads when pushing a virtual button.

2. Experiment

This experiment explored whether ultrasound tactile stimulus can intensify the perceived intensity of the pseudo-stiffness of a button in VR space.

2.1 Apparatus

The overall setup is shown in Figure 1. Four Airborne Ultrasound Tactile Displays (AUTDs) [7] were po-

図 1: Apparatus used in this study.

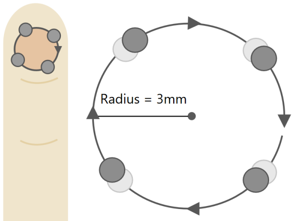

図 2: Foci of ultrasound stimulation.

sitioned at the bottom, with two on each side oriented vertically inward, totaling eight units. The AUTD was used to focus ultrasound on the participant's finger pad and present a noncontact tactile stimulus. All AUTDs were connected via EtherCat to a Windows computer for synchronized control. One depth camera (Realsense D415, Intel) was placed on the bottom of the rear side of the setup, and a hand-tracking camera (Leapmotion 2, Ultraleap) was placed at the front bottom. The VR space was constructed in Unity and displayed through a head-mounted display (Meta Quest 3, Meta) connected to the computer.

We used the hand-tracking camera to create virtual hands for inducing pseudo-stiffness of a virtual button and the depth camera to present ultrasound tactile stimulus to the finger pad. The hand-tracking camera collected 3D hand data and generated a virtual hand in virtual reality that can interact with virtual objects. The depth camera obtained point cloud data of participants' hands (3D position of finger pad surface). The contact position between the point cloud of the finger and the virtual button was identified, and then ultrasound tactile stimuli were presented to the 3D contact position.

Participants also wore the HMD and noise-canceling headphones to block external noise. Two virtual buttons were present in the center of the participant's field of view in the HMD. The right button in the center served as a reference, with a fixed C/D ratio of 1 (no pseudo-haptic effect) and no ultrasound stimulation. The left button was set with random experimental conditions(described in the next section); under certain experimental conditions, ultrasound stimulation was provided to the finger pad when it touched the button and stopped when the finger left the button.

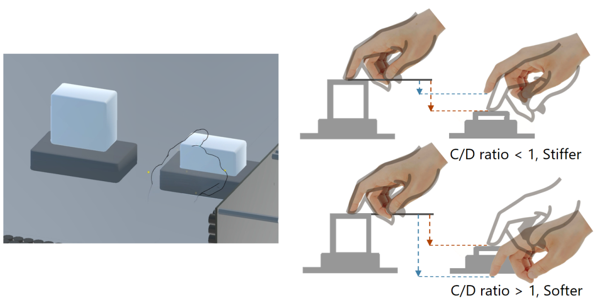

図 3: Schematic representation of pseudo-stiffness.

2.2 Stimulus Design

2.2.1 Ultrasound tactile stimulus

We simultaneously presented four ultrasound foci to the participant's finger pad and rotated them at 5 Hz to evoke static pressure sensation to replicate the sensation of pressing a button [8]. The stimulus design is based on a previous study conducted by Morisaki et al. [8]. They reported that 5 Hz focus rotation can evoke static pressure sensation rather than movement sensation and vibration sensation. The schematic of the stimulus design is shown in Fig. 2. Referring to the previous study, the radius of the focal trajectory was set to 3 mm and the space between the four foci was 3 mm.

We also used two types of ultrasound intensity modes: without ultrasound (none mode), constant maximum intensity (constant mode), and intensity increasing with displacement (increasing mode). In none mode, ultrasound tactile stimulus was not presented. In the constant mode, the amplitudes of ultrasound transducers were always maximum while presenting tactile stimulus. In the increasing mode, the amplitude was increased proportional to the y-directional finger displacement. The initial intensity was half of the maximum value.

2.2.2 Pseudo-haptics stimulus

To induce pseudo-stiffness perception, we altered the height of the buttons and the y-directional position of the virtual hand in the VR space (Figure 3). When the participant's virtual hand touched the virtual button, the y-directional position of the virtual hand was altered. The altered hand position $P_{\text{y\_Virtual}}$ is as follows:

$$P_{\text{y\_Virtual}} = P_{\text{y\_0}} + \alpha(P_{\text{y\_Real}} - P_{\text{y\_0}}), \qquad (1)$$

where $P_{\text{y\_Virtual}}$ denotes the altered y-directional hand position shown in VR space to induce pseudo-stiffness; $P_{\text{y\_0}}$ denotes the original y-position of the hand when touching the virtual button; $P_{\text{y\_Real}}$ denotes the y-position of the actual participant's hand; α denotes the C/D ratio.

We selected five different α for the experiment: 0.5, 0.8, 1, 1.2, and 1.5. When α is less than 1, participants perceive the buttons as stiffer. Conversely, when α is greater than 1 would make participants perceive the buttons as softer [3]. When α is 1, there is no alteration to the visual information, meaning no pseudo-stiffness effect.

2.3 Procedure

The experiment involved five participants, four males and one female, with an average age of 26.

Participants put on the HMD and noise-canceling headphones. Two side-by-side virtual buttons were shown to participants. The α of the left button was varied 0.5–1.5 as described in Section 2.2.2. The ultrasound tactile stimulus was also presented to the participants' finger pads when pressing the left button. The right button was used for reference stimulus and its α was always 1. Ultrasound tactile stimulus was not presented when pressing the right button. The participants first pressed the two virtual buttons and rated the perceived stiffness of the left button with a number between -10 and 10 by comparing the stiffness of the right reference button. If they perceived the left button was much stiffer compared to the right button, they responded with 10; if they felt it was much softer, they responded with -10; if they felt both buttons were almost the same, they responded with 0. After answering, the conditions were randomly switched, and the next trial began. Each participant performed two sets of experiments, resulting in a total of 30 trials ((5 α × 3 ultrasound intensity modes) × 2 sets) per participant. Finally, participants were asked to provide free comments.

2.4 Result

Figure 4 presents the perceived stiffness scores under different conditions of C/D ratio (α) and ultrasound intensity modes (UIM). The highest mean value of the stiffness perception score was observed under the condition of {$\alpha = 0.5$, UIM = constant and increasing mode}, and the lowest score (-8) appeared under the conditions {α = 1.2, UIM = increasing mode} and {α = 1.5, UIM = none mode}.

We conducted the Shapiro-Wilk test on the data, and the results indicated that 12 out of 15 groups followed a normal distribution ($p > 0.05$), while 3 groups did not: {$\alpha = 0.8$, UIM = increasing mode}, {$\alpha = 1$, UIM = none mode}, and {$\alpha = 1$, UIM = constant mode}. Based on the result, we decided to use a non-parametric method for the analysis. The Wilcoxon signed-rank test with Bonferroni correction was performed to compare different UIMs under the same C/D ratio conditions. The results showed that the presence or absence of ultrasound haptic stimulation significantly affected the perceived pseudo-stiffness under the following conditions: {α = 0.5, 1.5; UIM = none and increasing mode} and {α = 0.5, 0.8, 1; UIM = none and constant mode} ($p < 0.05$). Among the significant differences, the largest p-value ($p = 0.01563$) was found in the pair {$\alpha = 0.8$, UIM = none and constant mode}, and the smallest p-value ($p = 0.00586$) was found in the pair {$\alpha = 1.5$, UIM = none and increasing mode}.

図 4: Results of subjective experiments.

3. Discussion

The results imply that the addition of noncontact ultrasound tactile stimulus can intensify the pseudo-stiffness perception. Moreover, some participants commented that "the button with ultrasound haptics felt significantly stiffer."

Furthermore, there is no significant difference between the two ultrasound intensity modes (constant maximum intensity and intensity increasing with displacement) in terms of enhancing perceived stiffness.

In the free comments, some participants mentioned "feeling that their judgment and evaluation criteria changed during the experiment." This might be due to the experiment providing only one reference button with a stiffness score of 0 (C/D ratio = 1). In the future, for more stable evaluation, we will evaluate the pseudo-stiffness again with consideration of additional reference objects (e.g., the virtual button corresponding to a stiffness score of 10 and -10). We also plan to or provide practice sessions before the main experiment session.

Some participants commented that "overall, the judgment of the button's stiffness was still dominated by visual perception." This dominant effect of visual perception could be attributed to the uncontrolled pushing depth of the virtual button in the experiment. The virtual-real discrepancy in finger position in the push direction increases with the pushing depth, which might make the perception of pseudo-stiffness easier to notice. However, we did not control the pushing depth in the experiment. In the future, we will control the pushing depth and evaluate its effect on the stiffness perception of virtual buttons.

4. Conclusion

This study confirms that airborne ultrasound tactile stimulus can significantly intensify the perception of pseudo-stiffness. In the experiment, participants pushed a virtual button in VR space and evaluated its stiffness. When pushing the button, the pseudo-haptic effect and ultrasound tactile stimulus are presented. The results showed that the perceived stiffness of the virtual button with both ultrasound stimulus and pseudo-haptic effect was significantly higher than that with only the pseudo-haptic effect. In the future, we will evaluate the effect of pushing depth on the evoked stiffness perception.

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